LHCb Physics

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About this talk

• General introduction to the LHCb experiment, and its future.
• Physics program of LHCb is too broad to try to be complete today.
• Can’t even discuss all use cases of amplitude analyses, and range of amplitude formalisms used.
• Pick a few topics which fit together. Many biased by personal contributions to LHCb.
• Do not go deeply into discussion of the results or experimental details; concentrate on the approaches in the amplitude parameterizations illustrating material covered in the lecture today morning.
Evidence for Beyond Standard Model physics

- Unknown particles and forces exist, likely hiding at higher energy scales.
Evidence for Beyond Standard Model physics

Origin of hierarchy in masses and mixing of fermions?

12 orders of magnitude differences not explained; t quark as heavy as Tungsten

Why these values? Are the two related? Are they related to masses?
Two complementary ways of advancing “energy frontier” at accelerator-based experiments

Collision energy

Tree diagrams, for example

Loop diagrams, for example

Want high CM energy to exceed the production threshold

Heisenberg’s uncertainty principle:

$$\Delta E \Delta t = \hbar/2$$

i.e. $$\Delta m \Delta t = \hbar/2$$

Want high precision since NP particles are highly virtual here, thus probabilities small

(CDF, D0)

ATLAS, CMS

LHCb

Belle II (BaBar)

Rare kaon decays and “g-2” discussed by Andrzej Kupsc also belong to this category
Main physics goal of LHCb:

• A lot of secondary physics goals of LHCb:
  – Hadron spectroscopy with heavy quarks (see the next slide)
  – Light hadron spectroscopy
  – Rare kaon decays
  – W,Z⁰ production at forward angles and proton structure functions
  – Heavy-ion collisions
  – …
Heavy flavors and hadron spectroscopy:

All excitations above the open flavor threshold.
Wide (short-lived) and highly relativistic (light quarks).
Only qualitative spectroscopy.

Plenty of excitations below the open flavor threshold.
Narrow (long-lived) and non-relativistic (heavy quarks).
Quantitative spectroscopy.

Such fall-apart strong decays happen super fast, leading to a large mass indeterminacy i.e. large particle widths ("poorly formed" bound states)\[ \Gamma \cdot \tau \sim \hbar \]

Such strong decays take 1000 times longer.
Narrow widths; well formed bound states.
Well established spectroscopy of conventional hadrons with heavy quarks creates suitable environment for studies of exotic hadrons:

\[ Q\bar{Q}q\bar{q} \quad \text{tetraquarks or meson – meson molecules} \]

\[ Q\bar{Q}qqq \quad \text{pentaquarks or baryon – meson molecules} \]
Colliders and $b\bar{b}$ rates

- The past decade was a golden age of 10 GeV $e^+e^-$ b-factories
- Super KEK B-factory, with Belle II experiment, is under construction in Japan, with a luminosity upgrade by almost 2 orders of magnitude
Colliders and $b\bar{b}$ rates

- Tremendous rate potential at hadron colliders
  - Physics reach determined by the detector capabilities not by the machine
- Collect all $b$-hadron species at the same time:
  - Additional gain by a factor of $\sim 10$-100 in integrated $B_s$ rates at hadronic colliders
  - Time dependent CPV studies of $B_s$ possible
  - Also get $\Lambda_b$, $B_c$ which are out of reach of the 10 GeV $e^+e^-$ factories
- Charm rates factor of 10 higher than beauty rates:
  - Nuisance and great physics opportunity at the same time

Large challenge for $b,c$ physics at hadron colliders

\[
\int \mathcal{L} \, dt = \frac{N}{\sigma_{b\bar{b}}} \times \text{detector efficiency}
\]

\[
\varepsilon = \varepsilon_{\text{geometrical}} \cdot \varepsilon_{\text{trigger}} \cdot \varepsilon_{\text{rest}}
\]

LHCb Physics, T. Skwarnicki, Workshop on Reaction Theory, Bloomington, IN, 2017
CDF, D0, ATLAS and CMS were optimized to “high-$p_T$ physics” – searches for the heaviest on-mass-shell particles [ $m(\text{Higgs}) \approx 126$ GeV ].

Taking advantage of enormous rates of b,c-hadrons requires a detector optimized to “intermediate-$p_T$” particles [ $m(B) \approx 5$ GeV, $m(D) \approx 2$ GeV ].
Advantages of LHCb (forward spectrometer):

- comparable b cross-section in much smaller solid angle; smaller number of electronic channels; smaller event size;
- much larger trigger bandwidth to tape (Run I ~5 kHz, Run II ~12 kHz)
- b and c physics dominate the trigger bandwidth (e.g. CMS b-trigger rate ~25 Hz; almost 3 orders of magnitude less than LHCb)
- large $p_T$ for small $p_T$ (in central region $p_T \sim p$); can identify muons to lower $p_T$ values
- large bandwidth important for triggering on purely hadronic final states (central detectors limited to dimuon trigger)
- large bandwidth important for collecting very large charm samples
- space for RICH detectors: $p/K/\pi$ separation; crucial for background suppression in many channels; increased flavor tagging

Limitation of present LHCb detector:

- luminosity limited by the detector readout capabilities (upgrades of the detector will allow increasing the luminosity)
- compared to Belle: poor $\gamma$ (i.e. $\pi^0$) and $K_s$ detection (will be improved in Phase II upgrade)
LHCb collaboration

- The collaboration is of “modest” size:
  - 940 Physicists ($\sim \frac{1}{10}$ of all at CERN)
  - 70 Institutes ($\sim \frac{1}{10}$ in US)
  - 16 Countries
Loops as low energy windows to high energy physics

• An early example how decays of low mass particle can reveal physics at much higher mass scale was 1964 discovery of CP violation in $K^0$ decays ($m(K^0)=0.5$ GeV) which offered the first glimpse of the top-quark existence ($m(t)=172$ GeV, observed on-mass shell in 1995):

Quark-mixing elements $V_{qq}$ in $q \rightarrow q'W$ can be complex, only if more than two quark generations

Kobayashi-Maskawa hypotheses (1972)
Quark flavor transitions – CKM matrix

- Described by CKM matrix in SM
- A complex phase in 3-generation matrix gives a rise to CPV in SM
- Wolfenstein’s parameterization depicts the measured structure of CKM well

\[
\lambda = 0.226 \pm 0.001 \quad (\sin \theta_C) \\
A = 0.81 \pm 0.02
\]

\[
\rho, \eta \text{ see next} \\
\lambda^0 = 1 \\
\lambda^1 = 0.23 \\
\lambda^2 = 0.051
\]

Good to \( \lambda^3 \sim 1\% \)

\[
V = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A \lambda^3 (\rho - i \eta) \\
A \lambda^3 (1 - \rho + i \eta) & 1 - \frac{\lambda^2}{2} & -A \lambda^2 \\
-A \lambda^2 & -A \lambda^2 & 1
\end{pmatrix} + \delta V
\]

Complex phase \( \eta \)
mostly in \( V_{td} \), \( V_{ub} \) \( \lambda^3 \)
\( \lambda^3 = 0.012 \)
then a bit in \( V_{ts} \) \( \lambda^4 \)
\( \lambda^4 = 0.0026 \)
even less in \( V_{cd} \) \( \lambda^5 \)
\( \lambda^5 = 0.0006 \)
Quark flavor transitions – unitarity triangle

- After a decade of $e^+e^-$ B-factory experiments the KM hypothesis is well verified

\[ \rho = \rho(1-\lambda^2/2) \]
\[ \eta = \eta(1-\lambda^2/2) \]

Kobayashi & Maskawa
Nobel Prize 2008

- The game now is looking for NP in corrections to CKM picture

Trees: $\gamma, V_{ub}$
Loops: everything else
Importance of $B_s$ physics: example indirect CPV mixing

- Slow mixing, small CPV
  - CPV discovery
  - KM hypothesis

- Super slow mixing, very small CPV
  - Long distance diagrams can come into play
  - Good place to look for non-SM CPV, but SM “background” not well predicted

- Large mixing, large CPV
  - Good place to test SM CPV

- Super fast mixing, very small CPV
  - Good place to look for non-SM CPV
$B^0(s) - \bar{B}^0(s)$ mixing


$\Delta m_d = 0.5156 \pm 0.0051 \text{ (stat)} \pm 0.0033 \text{ (syst)} \text{ ps}^{-1}$

Single best measurement by BELLE

$\Delta m_d = 0.511 \pm 0.006 \text{ ps}^{-1}$

$B^0(s) - \bar{B}^0(s)$ mixing

charge of $\pi$ tags the $b$ flavor at decay

other $B$ tags the $b$ flavor at decay

$B_s \rightarrow B_s$

$B_s \rightarrow \bar{B}_s$

Decay time modulation

$\sim \cos(\Delta m_s t)$

$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \text{ ps}^{-1}$

**Phase of $B_s$-$\bar{B}_s$ mixing using $B_s \rightarrow J/\psi \phi$**

Interference of mixing and decay produces **indirect CPV**.

No SM phase in the lowest order. Small $V_{ts}$ phase suppressed by $\lambda^2$:

$$\phi^{SM}_s = -2 \arg \left( -\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} \right) \sim -2^\circ$$

$$[-36.5^{+1.3}_{-1.2}\text{ mrad, PRD91,073007 (2015)}]$$

Need **time dependent analysis** to extract $\phi_s$ from the data because $J/\psi \phi$ is a mixture of CP-odd and CP-even states, which have different $\phi_s$ dependence; need **angular analysis** to disentangle them.

$\phi \rightarrow K^+K^-$ (P-wave decay) is a **very narrow** and prominent resonance in $B_s \rightarrow J/\psi K^+K^-$, however, there is a small admixture of non-resonant $K^+K^-$ S-wave under it. Allow both contributions.
Determination of $\varphi_s$ from $B_s \rightarrow J/\psi\phi$

Use helicity angles.

Fit in the narrow $s=m_{KK}^2$ range around $m_{\phi}^2$

$$LHCb$ PRD 87, 112010 (2013)$$

<table>
<thead>
<tr>
<th>$k$</th>
<th>$f_k(\theta_{\Phi}, \theta_{S}, \varphi_S)$</th>
<th>$N_k$</th>
<th>$a_k$</th>
<th>$b_k$</th>
<th>$c_k$</th>
<th>$d_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2\cos^2\theta_K \sin^2\theta_{\Phi}$</td>
<td>$A_0$</td>
<td>1</td>
<td>$D$</td>
<td>$C$</td>
<td>$-S$</td>
</tr>
<tr>
<td>2</td>
<td>$\sin^2\theta_K (1 - \sin^2\theta_{\Phi} \cos^2\varphi_S)$</td>
<td>$A_1$</td>
<td>1</td>
<td>$-D$</td>
<td>$C$</td>
<td>$-S$</td>
</tr>
<tr>
<td>3</td>
<td>$\sin^2\theta_K (1 - \sin^2\theta_{\Phi} \sin^2\varphi_S)$</td>
<td>$A_{1\perp}$</td>
<td>1</td>
<td>$D$</td>
<td>$C$</td>
<td>$-S$</td>
</tr>
<tr>
<td>4</td>
<td>$\frac{1}{2}\sqrt{2} \sin 2\theta_K \sin 2\theta_{\Phi} \sin 2\varphi_S$</td>
<td>$A_0 A_1$</td>
<td>$C \sin(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$S \cos(\delta_1 - \delta_0) \cos(\delta_1 - \delta_3)$</td>
<td>$D \cos(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$D \cos(\delta_1 - \delta_3) \cos(\delta_1 - \delta_0)$</td>
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<tr>
<td>5</td>
<td>$\frac{1}{2}\sqrt{2} \sin 2\theta_K \sin 2\theta_{\Phi} \cos 2\varphi_S$</td>
<td>$A_0 A_{1\perp}$</td>
<td>$C \cos(\delta_1 - \delta_0) \cos(\delta_1 - \delta_3)$</td>
<td>$S \cos(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_0) \cos(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_3) \sin(\delta_1 - \delta_0)$</td>
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<td>6</td>
<td>$\frac{1}{2}\sqrt{2} \cos 2\theta_K \sin 2\theta_{\Phi} \sin 2\varphi_S$</td>
<td>$A_0 A_{1\perp}$</td>
<td>$C \cos(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$S \sin(\delta_1 - \delta_0) \cos(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_3) \cos(\delta_1 - \delta_0)$</td>
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<tr>
<td>7</td>
<td>$\frac{1}{2}\sqrt{2} \cos 2\theta_K \cos 2\theta_{\Phi} \sin 2\varphi_S$</td>
<td>$A_0 A_{1\perp}$</td>
<td>$C \cos(\delta_1 - \delta_0) \cos(\delta_1 - \delta_3)$</td>
<td>$S \sin(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_0) \cos(\delta_1 - \delta_3)$</td>
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<td>$A_0 A_{1\perp}$</td>
<td>$C \cos(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$S \sin(\delta_1 - \delta_0) \cos(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_3) \cos(\delta_1 - \delta_0)$</td>
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<td>9</td>
<td>$\frac{1}{2}\sqrt{2} \sin 2\theta_K \cos 2\theta_{\Phi} \sin 2\varphi_S$</td>
<td>$A_0 A_{1\perp}$</td>
<td>$C \cos(\delta_1 - \delta_0) \cos(\delta_1 - \delta_3)$</td>
<td>$S \sin(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_3) \cos(\delta_1 - \delta_0)$</td>
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<tr>
<td>10</td>
<td>$\frac{1}{2}\sqrt{2} \cos 2\theta_K \cos 2\theta_{\Phi} \cos 2\varphi_S$</td>
<td>$A_0 A_{1\perp}$</td>
<td>$C \cos(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$S \sin(\delta_1 - \delta_0) \cos(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_0) \sin(\delta_1 - \delta_3)$</td>
<td>$D \sin(\delta_1 - \delta_3) \cos(\delta_1 - \delta_0)$</td>
</tr>
</tbody>
</table>

$$A_0, A_{1\perp}, A_{1\parallel} (A_S)$$ related to helicity couplings $H_{S=\psi\phi}^{B_s\rightarrow\psi\phi}$, $\lambda_{\psi} = -1,0,1$ ($H_{S=\psi\phi}^{B_s\rightarrow\psi\phi}$ affected by the strong interactions, thus to be determined from the data (nuisance parameters).

See also LHCb PRL 114, 041801 (2015)
Many other sensitive probes for NP in weak decays of b and c quarks.

Move on to the results on exotic hadrons for the rest of my talk.
Other hadronic structures in $B_s \rightarrow J/\psi K^+K^-$


No evidence for horizontal bands, thus no sign of exotic $J/\psi K^+$ resonances
$B^0 \rightarrow \psi' \pi^+ K^-$

$\psi' \rightarrow \mu^+ \mu^-$

$Z_c (4430)^+ \rightarrow \psi' \pi^+$

Broad horizontal band

Kaon excitations

Claimed by Belle (the first $J/\psi \pi^+$ state):
PRL 100, 142001 (2008)
PRD 80, 031104 (2009)
PRD 88, 074026 (2013)
PRD 90, 112009 (2014)

Not seen by BaBar:
PRD 79, 112001 (2009)

LHCb has more than a factor of 10 larger data sample (3 fb$^{-1}$) than either Belle or BaBar and has smaller backgrounds
PRL 112, 222002 (2014)

Tetraquark or meson-meson molecule

Is it a reflection of interfering $K^*$'s $\rightarrow \pi^+ K^-$?
Proper amplitude analysis necessary to check
$\Lambda_b^0 \rightarrow J/\psi p K^-$: unexpected narrow structure in $m_{J/\psi p}$

$\Lambda(1520)$ and other $\Lambda^*$'s $\rightarrow p K^-$

LHCb PRL 115, 07201 (2015)
Similar statistics (26k events) and background level (~5%) as $B^0 \rightarrow \psi' \pi^+ K^-$

See also Nathan Jurik, PhD Syracuse, Aug 2016 CERN-THESIS-2016-086

Is it a reflection of interfering $\Lambda^*$'s $\rightarrow p K^-$?
Matric element for conventional resonances

$$\text{Prob} \sim \sum \Delta \lambda_\mu \left| M_{\Delta \lambda_\mu}^{K^*} \right|^2$$

4D maximum likelihood fit

$$\Omega \equiv (\theta_{K^*}, \theta_\psi, \Delta \phi_{\psi, K^*}, \Delta \phi_{\psi, K^*})$$

$$M_{\Delta \lambda_\mu}^{K^*} = \sum_n \sum_{\lambda_\psi=-1,0,1} H_{\lambda_\psi}^{B\rightarrow K^*} \sum_{\lambda_\lambda} \sum_{\lambda_\mu} \sum_{\lambda_\sigma} H_{\lambda_\lambda}^{L\rightarrow \lambda_\psi \lambda_\mu} D_{\lambda_\lambda, \lambda_\psi, \lambda_\mu}^{L\rightarrow \psi} \left( \Delta \phi_{\psi, K^*}, \theta_\psi \right)$$

1-3 independent complex helicity couplings $H$ per $K^*$ resonance

6D maximum likelihood fit

$$\Omega \equiv (\theta_{\Lambda_b}, \theta_{\Lambda^*}, \Delta \phi_{\Lambda^*_b, \Lambda_b}, \Delta \phi_{\Lambda^*_b, \Lambda_b})$$

$$M_{\Delta \lambda_\mu}^{\Lambda^*} = \sum_n \sum_{\lambda_\psi=-1,0,1} H_{\lambda_\psi}^{B\rightarrow \Lambda^*} \sum_{\lambda_\lambda} \sum_{\lambda_\mu} \sum_{\lambda_\sigma} H_{\lambda_\lambda}^{L\rightarrow \Lambda_b \lambda_\psi} D_{\lambda_\lambda, \lambda_\psi, \lambda_\mu}^{L\rightarrow \Lambda_b} \left( \Delta \phi_{\Lambda^*_b, \Lambda_b}, \theta_\Lambda \right)$$

4-6 independent complex helicity couplings $H$ per $\Lambda^*$ resonance

Use helicity amplitudes, now in wide range of $s=m_{K\pi}^2$ or $m_{Kp}^2$.

Approximate the $s$-dependence via a sum of Breit-Wigner amplitudes, each with independent complex helicity couplings.

This model is commonly used but has a number of theoretical shortcomings [desired properties of transition amplitudes are the subject of this workshop].
Model of conventional resonances

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th># of complex couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR</td>
<td>0$^+$</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>$K^*(800)^0$</td>
<td>0$^+$</td>
<td>682</td>
<td>547</td>
<td>1</td>
</tr>
<tr>
<td>$K^*(892)^0$</td>
<td>0$^+$</td>
<td>896</td>
<td>49</td>
<td>3</td>
</tr>
<tr>
<td>$K^*(1410)^0$</td>
<td>1$^-$</td>
<td>1414</td>
<td>232</td>
<td>3</td>
</tr>
<tr>
<td>$K^*(1430)^0$</td>
<td>0$^+$</td>
<td>1425</td>
<td>270</td>
<td>1</td>
</tr>
<tr>
<td>$K^*(1430)^0$</td>
<td>2$^+$</td>
<td>1432</td>
<td>109</td>
<td>1</td>
</tr>
<tr>
<td>$K^*(1680)^0$</td>
<td>1$^-$</td>
<td>1717</td>
<td>322</td>
<td>3</td>
</tr>
<tr>
<td>$K^*(1780)^0$</td>
<td>3$^-$</td>
<td>1776</td>
<td>159</td>
<td>3</td>
</tr>
</tbody>
</table>

Total # of free parameters: 28, 34

Well established states from PDG

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th># of complex couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda(1405)$</td>
<td>1/2$^-$</td>
<td>1405</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>3/2$^-$</td>
<td>1520</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td>$\Lambda(1600)$</td>
<td>1/2$^+$</td>
<td>1600</td>
<td>150</td>
<td>3</td>
</tr>
<tr>
<td>$\Lambda(1670)$</td>
<td>1/2$^-$</td>
<td>1670</td>
<td>35</td>
<td>3</td>
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<tr>
<td>$\Lambda(1690)$</td>
<td>3/2$^-$</td>
<td>1690</td>
<td>60</td>
<td>5</td>
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<tr>
<td>$\Lambda(1800)$</td>
<td>1/2$^-$</td>
<td>1800</td>
<td>300</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1810)$</td>
<td>1/2$^+$</td>
<td>1810</td>
<td>150</td>
<td>3</td>
</tr>
<tr>
<td>$\Lambda(1820)$</td>
<td>5/2$^+$</td>
<td>1820</td>
<td>80</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1830)$</td>
<td>5/2$^-$</td>
<td>1830</td>
<td>95</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda(1890)$</td>
<td>3/2$^+$</td>
<td>1890</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>$\Lambda(2100)$</td>
<td>7/2$^-$</td>
<td>2100</td>
<td>200</td>
<td>1</td>
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<tr>
<td>$\Lambda(2110)$</td>
<td>5/2$^+$</td>
<td>2110</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>$\Lambda(2350)$</td>
<td>9/2$^+$</td>
<td>2350</td>
<td>150</td>
<td>0</td>
</tr>
<tr>
<td>$\Lambda(2585)$</td>
<td>5/2$^-$</td>
<td>2585</td>
<td>200</td>
<td>0</td>
</tr>
</tbody>
</table>

Total # of free parameters: 64, 146

Large number of free parameters leads to problems with CPU, fit ambiguities

- A factor 2-4 more free parameters to fit in the $\Lambda_b$ analysis than in the B analysis
The models based on well-established conventional resonances (without or with exotics) describe these projections well:

- They dominate the rate
- If exotics present (as shown above) they spread across wide range of these masses
- A large number of free parameters in helicity couplings make up for deficiency of the model:
  - While all expected K* resonances in the fitted mass range are well established experimentally, there is a good reason to worry about missing Λ* resonances
Fitting decay angles important for resolving overlapping resonances

- They greatly increase discrimination power between resonances of different $J^P$
- Without using full decay phase-space difficult to do efficiency correction correctly

(Notice that if exotics are present, it is not possible to extract partial waves for conventional hadrons without a global fit to the data, which includes both conventional and exotic contributions)
Mass distributions sensitive to exotic hadrons

- We cannot describe $m_{\psi'\pi}$ or $m_{J/\psi p}$ distributions with the conventional resonances alone.
Matrix element for exotic resonances

\[ M^Z_{\Delta \lambda} = \sum_{\lambda} H^{Z \rightarrow \psi \pi}_{\lambda} R(m_{\psi \pi} | M^Z, \Gamma^Z) \]
\[ \times D^{JZ}_{\lambda \psi} \left(0, \theta \psi, 0\right) D^{1}_{\lambda \psi, \Delta \lambda} \left(\Delta \phi_{\psi, Z}, \theta^Z \psi, 0\right) \]

1 mass, 3 angles
all derivable from the \( K^* \) variables

\[ \left| M^{K^*} \left(m_{K^*}, \Omega | M^Z, \Gamma^Z, J^Z, A^{Z \rightarrow \psi \pi}, A^{B \rightarrow \psi K^*}\right) \right|^2 = \sum_{\Delta \lambda} \left| M^{K^*}_{\Delta \lambda} + e^{i \Delta \lambda} M^Z_{\Delta \lambda} \right|^2 \]

Additional rotations of spin states correcting for helicity frames for the final state particles (\( \mu, p \)) being different in s- and t-decay channels [Wigner rotations mentioned in Mikhail Mikhasenko’s lecture today]
Including exotic hadron contributions

\[ B^0 \rightarrow \psi' \pi^+ K^- \]

**LHCb**

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Fit frac. (%)</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z_c(4430)^+)</td>
<td>4475± 7±15-25</td>
<td>172±13±37-34</td>
<td>5.9±0.9±1.5-3.3</td>
<td>14σ</td>
</tr>
<tr>
<td>Belle</td>
<td>4485±22±28-11</td>
<td>200±46±26-35</td>
<td>10.3±3.5±4.3-2.3</td>
<td>5σ</td>
</tr>
</tbody>
</table>

\[ \Lambda_b^0 \rightarrow J/\psi \, pK^- \]

**LHCb**

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Fit frac. (%)</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_c(4450)^+)</td>
<td>4449.8±1.7±2.5</td>
<td>39± 5±19</td>
<td>4.1±0.5±1.1</td>
<td>12σ</td>
</tr>
<tr>
<td>(P_c(4380)^+)</td>
<td>4380±18±29</td>
<td>205±18±86</td>
<td>8.4±0.7±4.2</td>
<td>9σ</td>
</tr>
</tbody>
</table>

- **J^P=1^+** at 9.7σ incl. syst. (in Belle at 3.4σ)

- **Best fit has** \(J^P=(3/2^-, 5/2^+)\), also \((3/2^+, 5/2^-)\) & \((5/2^+, 3/2^-)\) are preferred. \((5/2^-, 3/2^-)\) cannot be ruled out within systematics.

The lack of clear \(J^P\) determination for the \(P_c\) states is troubling:

- Is underlying \(\Lambda^*\) “background” modeled properly?
- Is \(s\)- and \(t\)-dependence parametrization too naïve?
Argand diagrams: exotic hadron amplitudes without Breit-Wigner assumption

Exotic hadron amplitudes for $6 m_{\psi'\pi}/m_{J/\psi p}$ bins near the peak mass
(all other model parameters fitted simultaneously)

Good evidence for resonant character

Large errors

Need larger data samples, and good control of the model of conventional resonances, to make these studies more conclusive.

Such studies make exotic hadron amplitude model-independent, but the results are still dependent on the model of conventional hadrons. Simultaneous PWA of the latter is not possible since exotics reflect into variables characterizing conventional hadrons.

However, we can assume exotics are not present and test for their presence in model-independent way - next few slides.
Rectangular Dalitz plane: variables of conventional hadrons

- For fixed $m_{K\pi/Kp}$ there is one-to-one relation between $m_{\psi\pi/\psi p}$ and $\cos\theta_{K^*/\Lambda^*}$
Legendre moments

\[ \frac{dN}{d \cos \theta} = \sum_{l=0}^{l_{\text{max}}} \left( P_l^U \right) P_l(\cos \theta) \quad \theta = \theta_{K^*} \quad \text{or} \quad \theta_{\Lambda^*} \]

\[ \left< P_l^U \right> = \int_{-1}^{+1} \frac{dN}{d \cos \theta} P_l(\cos \theta) d \cos \theta \propto \sum_{i=1}^{n_{\text{events}}} \frac{1}{\epsilon_i} P_l(\cos \theta_i) \]

Decomposition into \( <P> \) corresponds to decomposition into “frequencies”

With \( l_{\text{max}} \to \infty \) can reproduce any \( \frac{dN}{d \cos \theta} \)

Smooth \( \cos \theta \) structures produce low rank moments

\( K^*/\Lambda^* \) can contribute only to low-rank moments

\[ l_{\text{max}} = J_1 + J_2 \quad \text{for interfering resonances} \]

In \( K^*/\Lambda^* \)-only hypothesis (\( H_0 \)) \[ l_{\text{max}} = 2J_{\text{max}} \]

\( J_{\text{max}} \) is the highest spin of \( K^*/\Lambda^* \) resonance possible

Reflections of exotic hadrons can contribute to low and high rank moments:

- Detecting non-zero moments above \( 2J_{\text{max}} \) signals presence of exotics
- The narrower the peak the higher the \( 2J_{\text{max}} \) required. The sensitivity is better for narrower exotic hadrons.
- Exotic hadron contributions spread over wide range of \( m_{K^*}/m_{Kp} \). An effective way of testing \( H_0 \) is to aggregate the information about \( \cos \theta_{K^*/Kp} \) moments in a function of \( m_{\psi'}/m_{J/\psi p} \).
Setting highest rank of Legendre moments

The sensitivity of the method improves by considering \( l_{\text{max}}(m_{K\pi}/m_{Kp}) = 2 \ J_{\text{max}}(m_{K\pi}/m_{Kp}) \) dependence:

it can be set from **known** \( K^*/\Lambda^* \) resonances, quark model predictions as a guide

**All predicted states are known!**

**Much fewer known states than predicted!**

- Because the \( J/\psi \) mass is smaller than \( \psi' \) mass, must allow for higher excitations in the \( \Lambda_b^0 \rightarrow J/\psi pK \) analysis, higher \( l_{\text{max}} \)

Known \( K^* / \Lambda^* \) states: boxes \( M_0 \pm \Gamma_0 \)

Mass range in \( \Lambda_b^0 \rightarrow J/\psi pK \):

- \( \Lambda^* \) mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001)

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K* mass predictions by Godfrey-Isgur, PRD 32, 189 (1985)

LHCb K* mass predictions by Godfrey-Isgur, PRD 32, 189 (1985)

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Illustrations using amplitude models of $\Lambda^0_{b} \rightarrow J/\psi pK^-$

Only exotic hadrons can contribute to excluded moments

The narrower the exotic hadron the better the sensitivity

- Disclaimers:
  - these are high statistics simulations to eliminate any statistical fluctuations (vertical scale is arbitrary)
  - exotic hadron contributions are usually only a few % fit fractions, thus the amplitudes of the red curves is expected to be small in the real data
Test the hypothesis \((H_0)\) that the data contain only conventional hadrons

Form a model of the data implementing this hypothesis:

\[
\text{PDF}(m_{K\pi/Kp}, \cos\theta_{K^*/\Lambda^*} | H_0) = F(m_{K\pi/Kp}) F(\cos\theta_{K^*/\Lambda^*} | m_{K\pi/Kp})
\]

\[
F(\cos\theta_{K^*/\Lambda^*} | m_{K\pi/Kp}) = \sum_{l=0}^{l_{\text{max}}(m_{K\pi/Kp})} \left \langle P^U_l \right \rangle (m_{K\pi/Kp}) P_l(\cos\theta_{K^*/\Lambda^*})
\]

\(B^0 \rightarrow \psi' \pi^+K^-\)

\(F(m_{K\pi})\)

\(\Lambda_{b^0} \rightarrow J/\psi \, pK^-\)

\(F(m_{Kp})\)
**Test H\(_0\) model on \(m_{\psi'\pi/\psi p}\) distribution**

\[
\text{PDF}(m_{\psi'\pi/\psi p} | H_0) = \int dm_{K\pi/Kp} \text{PDF}(m_{K\pi/Kp}, \cos \theta_{K^*/\Lambda^*}(m_{\psi'\pi/\psi p}) | H_0) \frac{\partial \cos \theta_{K^*/\Lambda^*}(m_{\psi'\pi/\psi p})}{\partial m_{\psi'\pi/\psi p}}
\]

\(B^0 \rightarrow \psi' \pi^+K^-\)

BaBar PRD 79, 112001 (2009)

BaBar did not have enough statistics to see \(Z(4430)\) this way.

Negative results like this impossible to interpret without amplitude analysis since \(Z-K^*\) interfere!

\(\Lambda_b \rightarrow J/\psi p K^-\)

PRL 117, 082002 (2016)

LHCb-PAPER-2016-009

LHCb data inconsistent with \(K^*\) contributions alone

LHCb data inconsistent with \(\Lambda^*\) contributions alone

This model independent proof of the presence of exotic hadron contributions is especially important for the \(\Lambda_b\) data, because of the difficulties in construction of a complete model of \(\Lambda\) excitations.
Rejection of $H_0$ can be quantified

Test variable: (quasi) log-likelihood-ratio

$$\Delta(-2\ln L) \equiv -2 \sum_{i=1}^{\text{num}} \ln \frac{PDF(m_{\psi\pi}|H_0)}{PDF(m_{\psi\pi}|H_1)}$$

$H_0: l_{\text{max}}(m_{K\pi})$  $H_1: l_{\text{max}}^{H1}=30$

This variable tests a significance of moments between $l_{\text{max}}(m_{K\pi\pi})$ and $l_{\text{max}}^{H1}$

PDF($\Delta(-2\ln L) \mid H_0$) $B^0 \rightarrow \psi' \pi^+ K^-$

PDF($\Delta(-2\ln L) \mid H_0$) $\Lambda_b \rightarrow J/\psi p K^-$

However, this approach cannot characterize exotics – amplitude analysis is still necessary.
Summary

• LHCb is the first hadron collider experiment optimized to heavy flavor physics, taking advantage of enormous b,c production rates

• Thanks to that it has unique data sets, and ambitious upgrade program, with data sample sizes to be increased by a factor of ~10 (100) in 10 (20) years.

• Searches for New Physics, as well as hadron spectroscopy studies often rely on complicated fits of amplitude models to the data

• It is possible, that some of our spectroscopic results are already limited by the choices of amplitude parameterization ($J^P$ of $P_c^+$ states?)

• Future searches for NP in loops may also require better amplitude parameterizations

• Some JPAC physicists are now directly affiliated with LHCb to help us cope with these problems